FURTHER EXPERIMENTS ON THE SEALING MECHANISM OF A SYNTHETIC RUBBER LIP TYPE SEAL OPERATING ON A ROTATING SHAFT

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The paper shows that a seal of the type referred to operates under hydrodynamic lubrication conditions with a liquid film thickness of obout 0·5 μm. Contact angles of oil against rubber and steel are measured, and it is also shown by experiments with capillaries how a meniscus may be turned inside out to resist pressure. The conclusion is that the liquid film is prevented from leaking by the surface tension of the liquid itself.

1 INTRODUCTION

ALTHOUGH SYNTHETIC rubber seals have been in use for more than 30 years and a great deal of research has been applied to their mode of operation, very little is known about the mechanism by which the sealing takes place. This is largely due to the difficulties of making direct observation on the film of oil which is known to be present between the sealing lip and the shaft.

Another difficulty as far as experimental work is concerned is the often inconsistent performance of seals; even under the most carefully controlled laboratory conditions it is sometimes impossible to obtain identical performance from two supposedly identical seals. It is difficult to induce leakage in a way which can be used to investigate the sealing mechanism since leakage at any time may be due to unknown factors.

2 EARLIER THEORIES

2.1 Face seals, rigid materials

Available literature on the sealing mechanism of seals is not extensive. Most of it refers to either practical or theoretical work on face seals and little of it relates to synthetic rubber. Iny (1)‡ considers that in the case of a face-seal sealing is achieved by an inward pumping action caused by waviness in the contact faces.

An alternative theory put forward by Kuzma (2) postulates once again that sealing is caused by an inward pumping action, but that this is due to deformation of the seal face caused by fluid pressure in the oil film. The treatment is purely theoretical and no practical evidence is put forward in support. Moreover there is little justification for assuming that the liquid film would penetrate only part way across the contacting seal faces.

Surface tension effects in the liquid have been advocated by several investigators as a possible sealing mechanism. It is among the parameters involved in the equation for sealing performance derived by Kuzma (2). Brkich (3) also considers that surface tension is significant.

2.2 Surface tension theories

Rajakovics (4) has presented a theoretical treatment in which he postulates that sealing is due to surface tension and is determined by the magnitude of the wetting angles between the lubricant and the asperities present on the seal surfaces. Jagger also favours surface tension as the basis of the sealing mechanism (5). He found that a coherent film of oil is always present under the seal lip and experiments included destruction of the meniscus by flooding the air side of the seal lip and by pressurization of the oil in the rig.

3 DEFICIENCIES IN THE OLDER SURFACE TENSION THEORIES

3.1 Lack of direct evidence

No one has yet devised experiments which measure quantitatively the effects of surface tension, probably because of the fact that all lubricating oils have a value of surface tension very similar to each other.

3.2 Pressurization experiment

If the oil film thicknesses and the pressures required to rupture the meniscus recorded in an early work (5) are checked against each other it is found that correlation is lacking by about a factor of 10.

3.3 Meniscus geometry

In recent years it has been popular among seal technologists to explain the effect of surface tension in terms of

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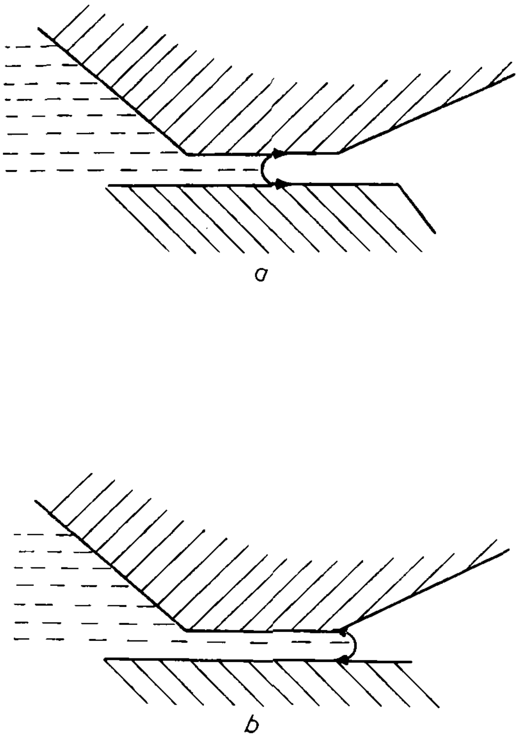


a Surface tension forces drawing oil into the capillary.
b Under pressurized conditions.

Fig. 1. The meniscus fallacy

the diagram at Fig. 1*b*. It is, however, manifestly impossible for such a state of affairs to exist in view of the known wetting angles of lubricating oils. Until more is known about the precise geometry of the meniscus the fallacy will remain.

3.4 Wettability of steel

Because of the high value of surface free energy of a steel surface the wetting angle of a lubricating oil is very nearly zero and this means that oil will spread freely on a steel surface. Some explanation of why the oil film stops at the end of the gap is required.

3.5 Rotating oil film

Since surface tension of a liquid is normally measured under static conditions there is some doubt about the applicability of these values to the conditions existing in an oil seal. Velocities and rates of shear can be high and it would be useful to know whether the value of surface tension under these conditions is appreciably different from the normally accepted values.

It is with all these various problems in mind that the present authors embarked upon the experimental work which follows.

4 EXPERIMENTAL—OIL FILM

4.1 Oil film measurements

A new type of thermocouple, described in reference (**6**), was used in conjunction with known techniques for measuring load, oil film thickness and torque of a nitrile seal running on a 3 in cylindrical shaft. The results are given in Fig. 2. Lip loading is not shown, as it was constant throughout the speed range.

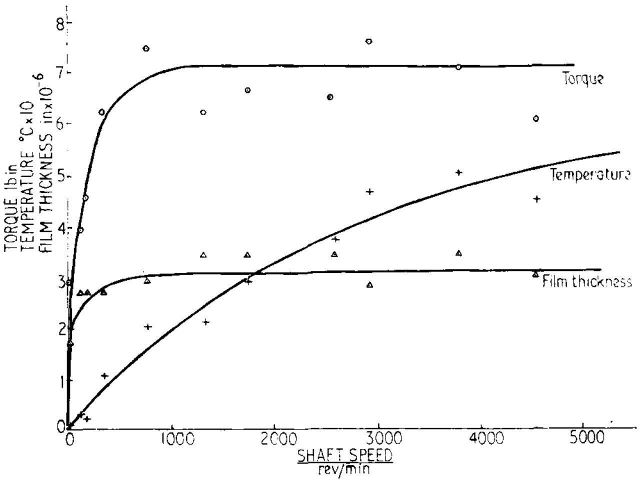


Fig. 2. Characteristics of a 3 in seal, oil-film thickness, torque and underlip temperature rise

Fig. 3 is plotted from the data and indicates that the oil film falls within the region of hydrodynamic lubrication through the whole of the speed range.

5 EXPERIMENTAL—SURFACE TENSION

5.1 Surface tension experiments

In order to ascertain the relevance of surface tension to the sealing mechanism the most logical experiment would be to run a seal with oils of varying surface tension and to measure the effect on leakage. However, since hydrocarbon

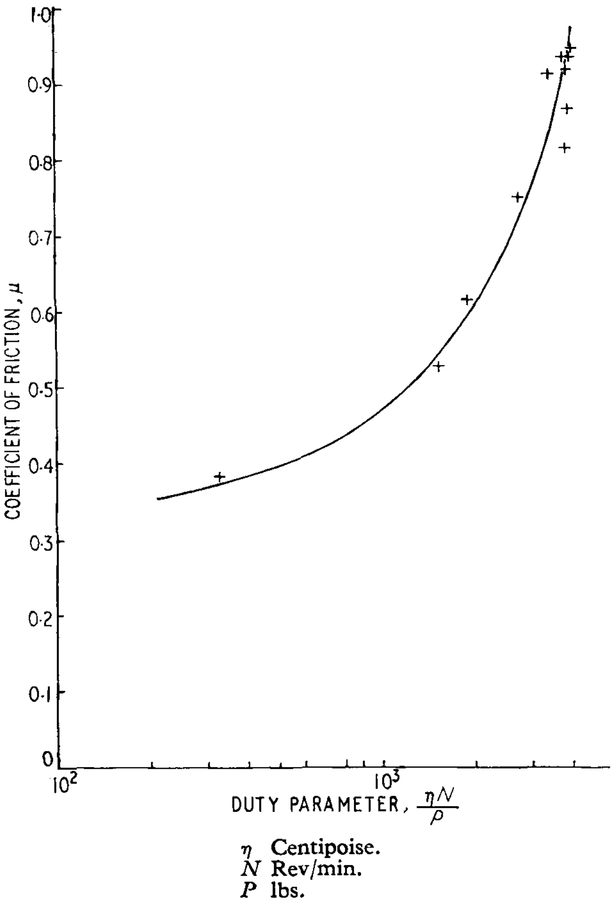


Fig. 3. Graph of friction against the duty parameter $\eta N/P$

oils consist of molecules whose attraction for each other is solely by means of Van der Waals forces, the surface tension is very low (about 30 dyn/cm) and cannot be reduced. Addition of an electrolytic solvent to raise the surface tension is also not possible because of the insolubility of ionic molecules in hydrocarbons.

An alternative method would be to use an oil–aqueous interface whose interfacial tension can be varied by the addition of surface active agents which generally take the form of long chain organic molecules with an ionic group at one end. By the use of various concentrations of surface active agent the oil-water interfacial tension can be reduced from around 50 dyn/cm to less than 1 dyn/cm. It was decided to run a seal with oil on one side of the seal lip and water with varying concentrations of surface active agent on the other. The leakage, interfacial tension and contact angles between the oil, water and solid surfaces were measured for each concentration of surface active agent used. The apparatus used is shown in Fig. 4; this is a modification of a test machine used extensively in the past by one of the present authors. The modifications consisted of reducing the seal diameter to 3 in and of adding a reservoir at the outside to contain the water. The seal was moulded from a nitrile rubber with a contact band width of 0·040 in. Speed was maintained constant at 500 rev/min. There was no oil circulation and no artificial heating or cooling. The total load on the seal was 1·41 kg. The test procedure was to run the rig with oil only (on the inside) for 1 h to ensure that the seal was sealing correctly; the outside compartment was then filled with distilled water and run for another 1 h. If there was no leakage the test was continued by adding a small amount of surface active agent (Glover's Chemicals product 'Catafor 09', an ethoxylated amine). A sample of the aqueous phase was taken at this time for measurement of interfacial tension and contact angles against rubber and metal. The rig was then run for 4 h after which time it was examined for leakage; in all cases it was found that water had leaked towards the oil side of the seal. The water appeared as an emulsion and the leakage was quantitatively assessed by distilling off the water from a weighed sample of the oil–water emulsion.

The interfacial tension between the oil and aqueous solution was measured by the pendant drop method devised by Andreas, Hauser and Tucker (7).

The contact angles between water–oil–rubber and water–oil–metal surfaces were determined by immersing a rubber or steel block in oil and depositing a drop of water from a syringe on to the solid surface. After leaving the drop for about an hour to reach a state of equilibrium a photograph was taken and the contact angle determined from it.

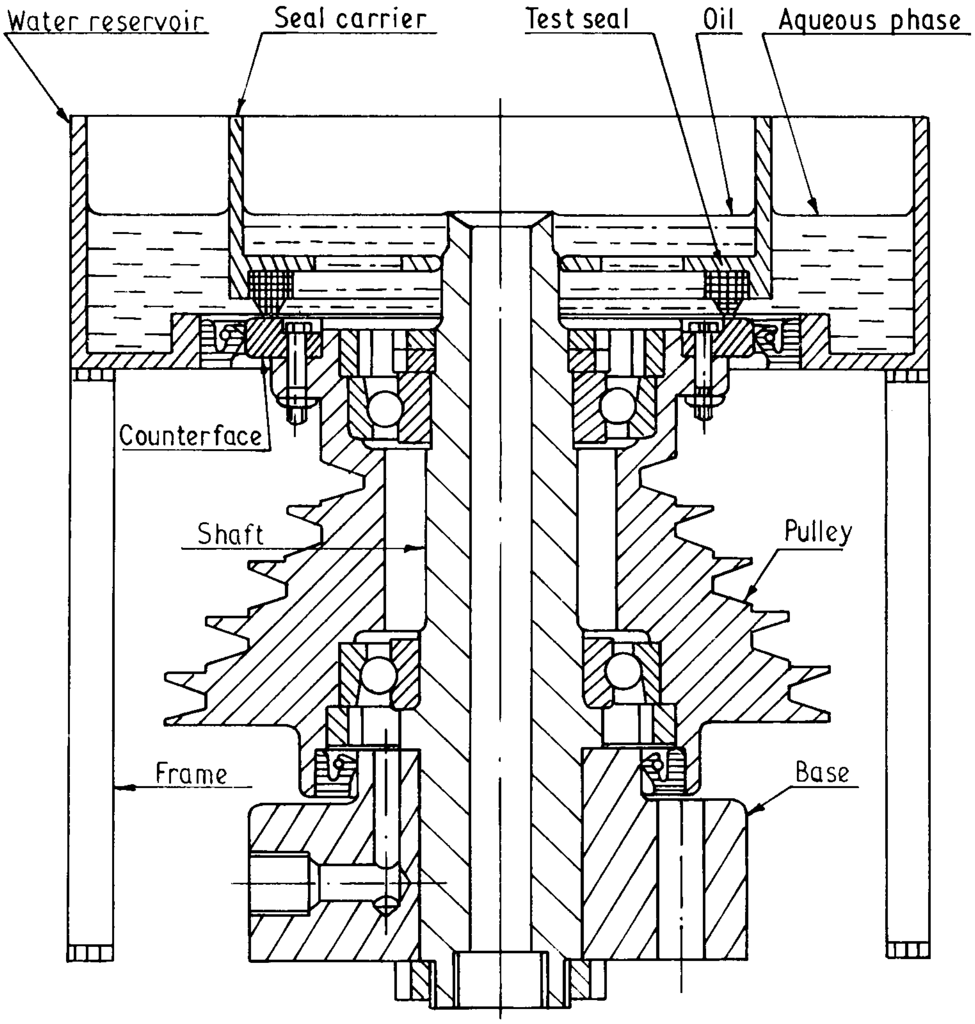


Fig. 4. Apparatus used for the work on surface tension

Leakage was plotted against these variables and the results are shown graphically in Figs 5 and 6. Fig. 5 shows that leakage increases as the interfacial tension is reduced; Fig. 6 shows that leakage is also dependent on contact angle, increasing as contact angle increases.

Calculation shows that centrifugal effects under these conditions are small but a test was run to confirm that centrifugal forces were not accounting for the leakage. This test was run with oil on the outside of the seal and the aqueous phase with a high concentration of surface active agent on the inside. It was found that water was still transferred to the oil side of the seal and at a greater rate than in the previous tests.

5.2 Discussion of results

Two aspects of these results merit further discussion; the first relates to their general significance in the context of the sealing mechanism and the second relates to the question of why the water should leak into the oil rather than as might be expected, the reverse.

In very general terms it can be said that the results show that sealing performance is influenced by the surface tension of the fluids involved. In these experiments we are dealing with an oil–water interfacial tension, but a similar situation would exist if the water were substituted by the more normal air; in this case we would be dealing with the oil–air surface tension and sealing performance would be affected in a similar manner.

5.3 Surface tension contact angle and wettability

In this context it is immaterial whether we use the term surface tension or surface free energy; they are interchangeable. Fig. 7 illustrates the situation at an oil–water–rubber contact. γ denotes surface tension or surface free energy difference and the various suffixes indicate the particular interface concerned. At equilibrium the system obeys the Young–Dupré equation, $\gamma_{WR} = \gamma_{OR}+\gamma_{OW} \cos \theta$. This transposes to the form shown in the diagram and indicates that the contact angle depends on the various surface free energy differences. In the case of the materials shown γ_{OW} and γ_{WR} have a high value and γ_{OR} has a low value. Hence cos θ will be large, the angle θ will be relatively small and the tendency will be for the oil phase to spread along the surface of the rubber, displacing the water phase.

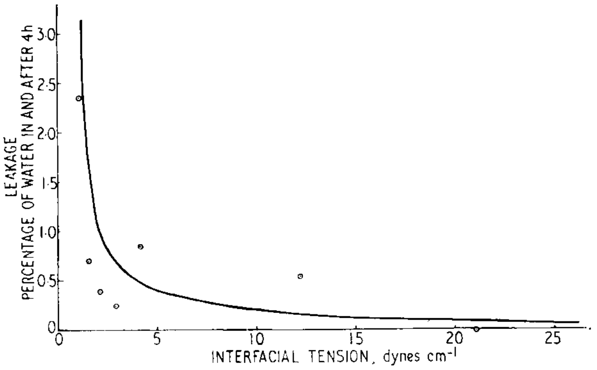


Fig. 5. Graph showing dependence of leakage on the value of interfacial tension between the sealed fluid and the external fluid

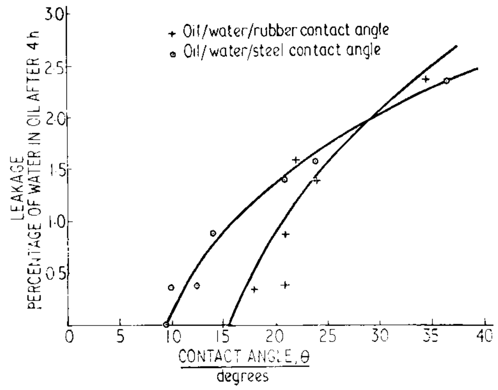
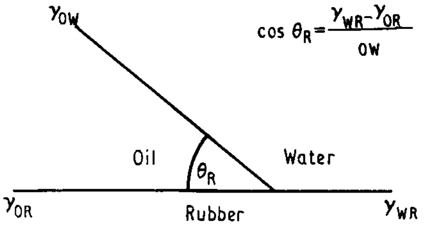


Fig. 6. Variation of leakage with contact angle



θ_R is contact angle.
γ is the surface free energy difference at interface.

Fig. 7. Conditions at an oil–water–rubber contact

5.4 Effect of surface active agent

When surfactant molecules are added they are adsorbed at the various interfaces and the result of this is that γ_{OW} and γ_{WR} are significantly reduced while γ_{OR} will be little changed. The net result is that cos θ becomes smaller and the angle θ increases, hence the tendency for the oil to displace the water is reduced.

5.5 Steel surface

Experiments described later in this paper have shown that the steel surface is always contaminated by an adsorbed layer which gives it similar surface properties to the rubber surface and hence the remarks of the previous paragraph apply in this case also. A fuller explanation of the chemical aspects of this situation can be found in (**8**).

5.6 Water leakage

The interfacial tension is reduced and the contact angle increased with increasing concentration of surfactant. The corresponding increase in leakage of water to the oil side of the seal can now be explained on the basis of the reduced wetting ability of the oil which can be regarded as an increased wetting ability of the water.

However, it is debatable whether in a static situation this increase in wetting ability of the water would result in leakage; but the vibration and movement of the practical situation cannot be ignored. It is clear that under running conditions the oil film will periodically thicken because of vibration and momentary rupture of the meniscus will continuously be taking place. At these instants of rupture a transfer of water to the oil side of the seal could occur.

6 PRESSURIZATION CALCULATIONS

Work carried out by one of the present authors several years ago led to the conclusion that the oil film between the sealing lip of a rubber seal and the shaft is 'of the order of 1×10^{-6} in thick'. This value is about 2·5 μm but because of problems of calibration at that time no claim for accuracy better than about an order of magnitude was made.

However, Fig. 2 indicates that a typical value for the oil film thickness is about 0·5 μm or 5 times smaller than was previously considered. By accepting for the present the 'meniscus fallacy' illustrated in Fig. 1*b*, and then making calculations on the conventional basis, it is found that the rupture pressures quoted in reference (5), instead of being about eight times too large, are much more reasonable.

This disposes of one of the problems associated with the surface tension theory of sealing.

7 CONTACT ANGLE EXPERIMENTS

Since the shape of the meniscus and hence its ability to influence the sealing mechanism depends for a given film thickness on the contact angle which oil makes with rubber and with steel a programme of work relating to contact angle measurement was undertaken.

In all cases the measurements were made by depositing a drop of liquid from a micro syringe on to the surface under examination and photographing the equilibrium position of the drop; this enabled direct measurement of contact angle to be made. In some cases, where comparative values only were needed, water was used instead of oil.

7.1 Synthetic rubber

Numerous measurements were made using oil on nitrile synthetic rubber without artificially cleaning the surface and results were typically around 20°.

7.2 Steel

Several samples of steel obtained from various sources in the laboratory, the technical offices and the works were used for contact angle measurements and with oil the value obtained was typically about 10°. This was an unexpectedly high figure since the very high surface free energy of steel should lead to a contact angle approaching zero. It was considered that the high value must be due to surface contamination and therefore a further series of experiments was undertaken to investigate this point.

7.3 Chemically clean running conditions

The contact angle of a water drop was used to assess the degree of contamination of a steel surface.

A stainless steel counterface was lapped and polished to a fine finish. The contact angle of a drop of water on the metal was measured and found to be about 75°, the metal obviously being contaminated (probably by the oil used with the lapping compound). The counterface was fitted to the vertical spindle rig, wiped with alcohol and then heated with a gas torch for several minutes until a drop of water deposited on the surface spread and exhibited a contact angle of less than 10°. This surface was accepted as 'clean'. The seal was then fitted and a sleeve around the outside enabled the space at the air side of the seal and counterface to be purged with nitrogen and run in a nitrogen atmosphere. The rig was filled with oil and run for two hours and after this time a contact angle measurement (outside the sealed area) with a drop of water gave a value of about 75°. It was concluded that oil had spread from the oil film under the contact band, probably in the form of a monolayer, and contaminated the metal surface.

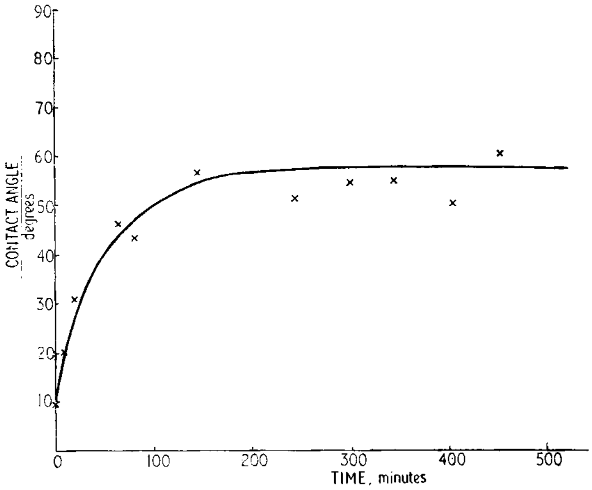


Fig. 8. Contact angle of water on steel

The contamination of a steel block exposed to the atmosphere is shown in Fig. 8. The surface quite quickly became contaminated and after about 1·5 h it had a contact angle similar to the various steels tested earlier. These results have great significance in explaining the sealing mechanism.

8 MENISCUS EXPERIMENTS

8.1 Meniscus at a suddenly widening gap

The situation depicted in Fig. 1*a* is unstable since the capillary forces which have drawn oil into the gap will continue to draw the oil forward and we know from experiments with seals running on glass cylinders that the oil completely fills the width of the gap. What is not clear is why the oil film stops at the outer edge of the gap instead of continuing to flow along the steel and 'around the corner' of the rubber surface.

The work just described on contact angles with steel indicates that it is at least possible for the oil to stop spreading over the steel surface and the fact that the gap suddenly widens is probably enough justification for saying that capillary action will cease. A simple experiment can throw more light on this question.

The meniscus formed by oil in a glass capillary tube was studied by holding the tube vertically with the open end upwards and causing the oil to rise to the top of the tube by manipulating a syringe attached to the other end. A camera was focused on the top of the capillary tube which was ground and polished to a fine finish. When the meniscus was moved to the top of the tube, as shown in Fig. 9*a*, the oil declined to turn the corner and spread over the top surface. As pressure was increased the meniscus became flatter (as in Fig. 9*b*) and then became convex, the convexity increasing with pressure as shown in Figs 9*c*, *d* and *e*. Only after a further considerable increase in pressure did the oil turn the corner and begin to spread across the top surface of the tube as shown in Fig. 9*f*.

This simple experiment establishes the fact that in the case of an oil seal the oil film can be drawn across the full

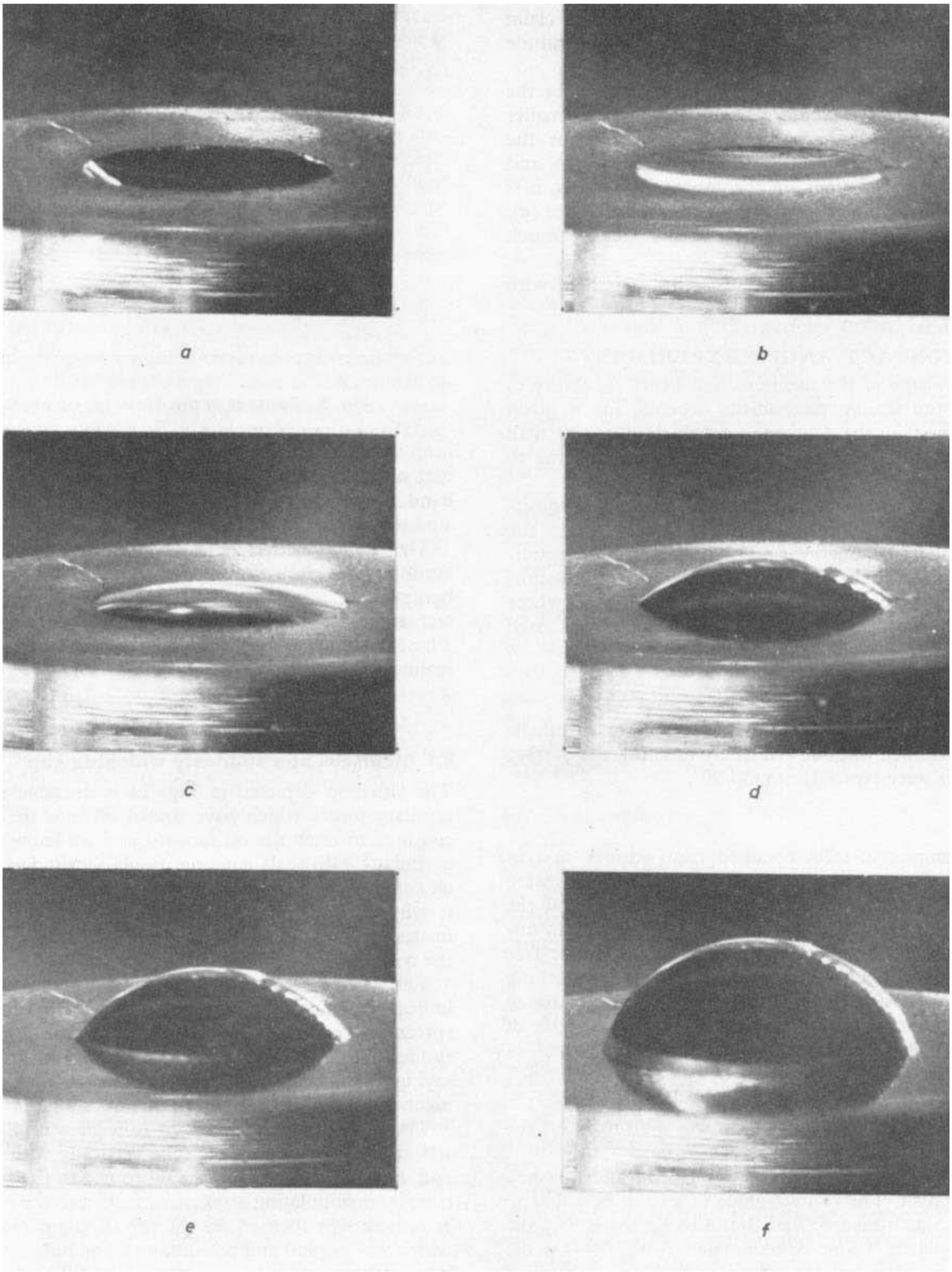


Fig. 9. Photographs showing the reluctance of liquid in a capillary to travel beyond the point where the capillary ends

width of the seal contact area, but that it will stop at the outer edge where the gap widens unless driven further forward by pressure in the oil film.

However, it still leaves unexplained the fallacy of Fig. 1*b*, since we know that the contact angles are around 20° (in the oil phase) and that the 180° shown in Fig. 1*b* is an impossibility. A further simple experiment was designed to throw more light on this important aspect.

8.2 Meniscus turning inside out

Many experiments were carried out with capillary tubes containing liquid–liquid and liquid–air interfaces. A de-

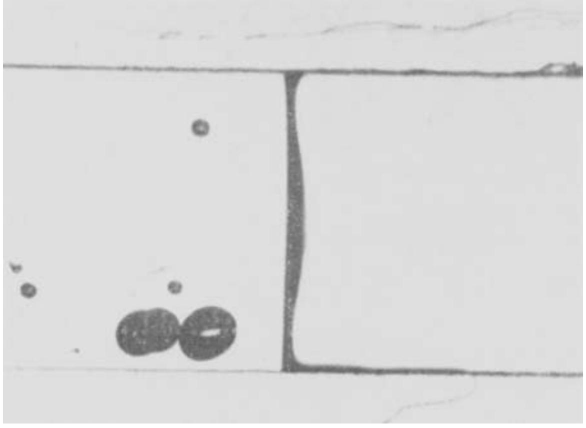


Fig. 10. Meniscus in a capillary just beginning to turn inside out

tailed study revealed that it was indeed possible to turn the meniscus inside out under the application of pressure. It was found that at the actual point of contact with the glass surface the contact angle was unchanged. The convexity commenced a little way from the surface at a point of inflexion where the slope changed from positive to negative.

This result is indeed startling and serves to explain completely the meniscus fallacy indicated in Fig. 1. The photograph in Fig. 10 is typical of many experiments which were made.

9 ROTATING OIL FILM

One final question remains for comment; this is the question of surface tension effects in a dynamic situation as opposed to the normal static one.

A study of the literature reveals that some work carried out in France by Borneas and Babutia (9) may be relevant. They found that movement of a liquid in either rotary or rectilinear motion had negligible effect on the value of its surface tension. The speed used was only about 1/8 of the surface speed used here, but it is felt that the result is a useful pointer.

10 CONCLUSION

The work described in this paper adds more weight to the view that the surface tension of the sealed fluid plays a most significant part in the mechanism of sealing in the situation under discussion, namely the case of a synthetic rubber lip type seal running on a rotating shaft.

Investigations into the variation of leakage with interfacial tension and contact angle using an oil–water interface have shown that reduction in interfacial tension results in a marked increase in leakage. This is due to reduction in the surface free energy differences between the oil, water and solid interfaces. It is proposed that a similar situation will occur in the case of a normal oil seal running with an oil–air interface and that surface tension is the force which controls leakage. This force will be affected by pressure in the oil film and by fluctuations in oil-film thickness caused by such factors as vibration, eccentricity, lip damage, permanent set or hardening of the rubber and damage to the shafts.

Contact angles of oil against synthetic rubber and steel have been determined and it has been shown that under all practical operating conditions the contaminated surface of steel has a contact angle much higher than expected; high enough in fact to prevent spreading of the sealed oil along the surface of the steel shaft.

The 'meniscus fallacy' has been fully explained and it has been demonstrated that a meniscus can be turned inside out by the application of pressure without contravening the fundamental laws of surface physics.

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APPENDIX

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